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FEB 81 V ZAKKAY, V BARRA AFOSR-79-0128
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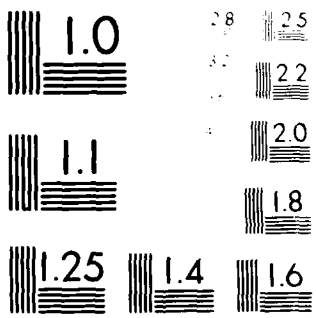

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NEW YORK UNIVERSITY
FACULTY OF ARTS AND SCIENCE
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(12) LEVEL II

NYU/DAS-81-23

THE INVESTIGATION OF THE PROPAGATION MECHANISM OF PRESSURE FLUCTUATION IN TURBULENT FLOW

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FINAL REPORT

AFOSR-79-0128

FEBRUARY 1981

NEW YORK UNIVERSITY

FACULTY OF ARTS AND SCIENCE

DEPARTMENT OF APPLIED SCIENCE

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ABSTRACT

A summary of the work performed under Contract AFOSR-79-0128 is given within this report.

Under this Contract, the Antonio Ferri Laboratories at New York University has built a one foot induction wind tunnel for the purpose of studying the coherent structure of turbulence. Simultaneous measurements of velocity, wall pressure and wall-shear fluctuations were made on the wall of a one foot pipe in a range of velocities from 30 to 700 ft/sec.

The results presented here were obtained for flow conditions which differ significantly from those in previous studies. For the majority of the tests, the free stream velocity is in the high subsonic regime, and the Reynolds number is an order of magnitude higher than that for which the coherent structure has previously been investigated. The measurements were made on the wall of an axially symmetric one foot test section in order to insure true two-dimensionality of the flow.

The results of the above research has been reported in six technical reports which have been published in the open literature. A sumary of this work is presented in this report.

INTRODUCTION

Boundary layer skin friction drag of aircrafts accounts for approximately 50% of the total vehicle drag. During the past decade, several schemes have been tried in order to control the boundary layer on these vehicles, and therefore be able to reduce the drag. The boundary layer over these vehicles is predominantly turbulent, and it is only through the understanding of how turbulence is generated, and propagates, that one will be able to control turbulence and therefore achieve drag reduction.

The discovery, during the past decade, by means of visual observations (Refs. 1-7) of an organized structure in turbulent shear flows has led to a proliferation of new measurement and data analysis procedures for the investigation of the flucutating properties of such flows (Refs. 8-19). Questions have been raised concerning the adequacy of measurements which utilize instrumentation and analyses not suited to the coherent, quasi-periodic nature of the flow structures. It has been found that the size of the transducers used in the measurements and the frequency response of the associated electronics is an important consideration in terms of the varied scales of the flow structures; and that single point measurements and conventional time averaged analyses cannot reveal much useful information about coherence or intermittency both of which are important aspects of the flow processes involved.

To overcome these problems, modern research efforts have turned to minituarized instrumentation and multiple measurements to obtain spatial resolution

of the coherent flow structures, and to digitization of the measurements so as to allow various time series to be performed on high speed computers. With respect to the latter, it has become increasingly popular to apply various conditional sampling procedures to the digitized fluctuations in order to isolate temporal sequences associated with the coherent structures. This type of analysis has revealed, among other things, that significant contributions to the long time average Reynolds stress occur during intervals when coherent structures are present in the flow, thus indicating that the modelling of turbulence and the development of drag and noise reduction mechanisms might benefit greatly from a better understanding of these structures.

Visual observations of turbulent boundary layer flows seeded with various tracers have indicated the presence of several different processes involving repetitive flow structures. The wall region ($y^+ = y\, u_\tau/\nu < 100$) is characterized by streamwise streaks of low speed fluid which lift up from the wall resulting in locally inflexional velocity profiles. The lift-up is followed by some sort of oscillatory motion and then a sudden breakup into small scale turbulence. The injection of low speed fluid from the wall is accompanied by sweeps of high speed fluid from the outer regions toward the wall. This overall process has been referred to as a "burst" (Refs. 20-21). On a larger scale, the boundary layer is dominated by vortical structures which extend to the viscid-inviscid region (Refs. 6, 14, 16). The relationship or interaction between this large-scale outer structure (LSOS) and the turbulent "bursts" is still not clearly defined. In particular, how these processes and their relationship change with

increasing Reynolds number has not been fully explored. On the basis of observations and measurements over a limited range of Reynolds numbers, it has become commonly accepted that the "bursting" process is strictly a sublayer phenomenon that scales with wall variables, while the large-scale outer structure is basically Reynolds number independent. A possible link between the two processes may exist in the fact that the frequency of occurrence of the turbulent "bursts" has been found to scale with outer flow variables and seems to be related to the period of passage of the outer structures (Refs. 22-23).

The primary goal of this research has been directed to study these phenomena at a high subsonic speed, and to specifically determine the possible role or influence of pressure fluctuations on the processes involved. Whereas most studies in this area tend to be at relatively low free stream velocities (typically, $U_\infty < 100$ ft/sec) and Reynolds numbers ($Re_\theta < 10^4$), the present results are for a turbulent boundary layer with $U_\infty = 675$ ft/sec and $Re_\theta = 108{,}000$. In addition, simultaneous measurements of three properties of the turbulent flow, namely, the streamwise velocity, the wall shear and the wall pressure were made. Preliminary results from measurements at $U_\infty = 675$ ft/sec led to the conclusion that it would be of some value to have comparitive measurements at lower velocities. Therefore measurements for boundary layers with $U_\infty = 73$ ft/sec and $U_\infty = 32$ ft/sec were also made, and are presented for comparison.

EXPERIMENTAL FACILITIES AND PROCEDURES

The New York University one foot diameter induction tunnel developed under this contract was used for this research. The facility has been described in detail in Refs. 19 and 24. The wind tunnel has the capability of varying the velocity from 30 to 700 ft/sec. In addition the wind tunnel was modified so as to allow the test section to be located at several distances from the inlet of the tunnel. This allowed the measurements to be made at various distances from the inlet depending on the boundary layer thickness required (at the lowest velocity, a boundary layer thickness of 3" was reached within 15 ft of the tunnel inlet).

The development of the data gathering system and the analysis program has been a major part of the research program (see Ref. 19). The system has been greatly improved by the acquisition of a PDP-11/34 mini-computer and a 14 channel tape recorder. The mini-computer system includes 64K bytes of memory, two terminals - one of which is an interaction CRT graphics terminal, floppy and cartridge disk mass storage, and most significantly, a 64 channel A/D converter with two programmable clocks. Programs have been developed on this system which are capable of performing the following analysis on a production run basis:

1) Long-time average auto and cross correlations.
2) Conditional sampling using the variable interval time average (VITA) variance (see Kaplan and Laufer (Ref. 25) or Blackwelder and Kaplan (Ref. 8)).

3) Pattern recognition analysis to compensate for random phase "jitter" in conditional sampling (see Blackwelder (Ref. 26)).

4) Short-time, conditionally sampled auto and cross correlations (see Brown and Thomas (Ref. 14)).

These analyses can be applied directly to the original digitized data or to the data after it has been filtered using the Fast Fourier Transform to include only components within a chosen bandpass. In this way it should be possible to determine the importance or influence of different frequency ranges on particular results. From the use of the different analyses it should also be possible to determine if different approaches to conditional sampling produce comparable results when applied to the same data.

Test Conditions

In Ref. 19 experimental results were presented for $U_\infty = 675$ ft/sec. Extensive mean and fluctuating flow measurements at $U_\infty \approx 75$ ft/sec and $U_\infty \approx 30$ ft/sec have also been made. The mean flow properties of the boundary layer at several stations along the tunnel for these three flow conditions are summarized in Table I. Simultaneous measurements of the fluctuations have been made primarily with the sensor array shown in Fig. 1 and more recently with that shown in Fig. 2. In the latter, six wall-shear measurements are oriented so as to yield information about the turbulent structure in the lateral directions. The present results are for data from the following test conditions:

- $U_\infty = 675$ ft/sec, X/D = 31, Both arrays (i.e., Figs. 1 and 2)
- $U_\infty = 73$ ft/sec, X/D = 15.5, Fig 1 array only

- U_∞ = 75 ft/sec, X/D = 20.5, Fig. 2 array only
- U_∞ = 32 ft/sec, X/D = 20.5, Both arrays

The aim of these tests is to yield data over a wide range of Reynolds numbers (i.e., from approximately 5000 to 100,000) while maintaining the boundary layer thickness in the neighborhood of 3 to 4 inches. The friction velocity, an important parameter in terms of the wall layer, also taken on a wide range of values for these tests, that is, from 1.8 ft/sec to 18 ft/sec.

DESCRIPTION AND DISCUSSION OF THE WORK PERFORMED

The experimental facilities, instrumentation and data analysis have been described in detail in Refs. 19, 24, and 27.

Streamwise Results

A sample plot of digitized fluctuations is presented in Fig. 3. Approximately 42 ms ($t\, U_\infty/\delta^* = 588$) or 8400 data points are shown for each of the nine fluctuating quantities. Using the symbol α to represent one-half of the vertical distance between adjacent zero lines in Fig. 3, the vertical scales of the plot are as follows: 1) for the velocity fluctuations $\alpha = 0.13\, U_\infty$, 2) for the shear fluctuations $\alpha = 0.27\, \rho U_\tau^2$, and 3) for the pressure fluctuations $\alpha = 0.24\, q_\infty$. A great deal of readily observable correlation can be seen at various times across parts or all of the measurement grid. The time $t = 0$ marks the approximate location of one event in the data as determined by applying the VITA variance analysis to the velocity at $y/\delta^* = 0.088$. For this particular event, the detection scheme also triggers on the wall shear (at $t \approx + 5\mu s$) and the four other velocity measurements (at $t \approx - 120$, $- 210$, $- 275$, and $- 330\mu s$ moving away from the wall).

A sequence of velocity fluctuation profiles centered about the time $t = 0$ are shown in Fig. 4. The entire sequence is for an interval of 700 μs ($tU_\infty/\delta^* = 10$). Also shown at each time is the instantaneous shear fluctuation on the wall as measured by the flush mounted hot-film sensor. It may be of

interest to note that the development of the velocity fluctuation profiles during this sequence shows some similarities to the "bursting" event as depicted by investigators doing both theoretical[24] and experimental[11] work. In particular, the profiles shown in Fig. 4 and those obtained by Blackwelder and Kaplan (Ref. 8, Fig. 5) in the wall region of a boundary layer with U_∞ = 4.27 m/s (14 ft/s) and Re_θ = 2550 seem to indicate the occurrence of similar flow processes. A shear layer, with positive fluctuation velocities above and negative velocities below, first appears in the outer measurements and moves toward the wall. The region of negative fluctuation velocities undergoes a deceleration followed by a rapid acceleration which combined with the movement of the shear layer toward the wall results in positive fluctuation velocities at all the measurement positions. The rapid acceleration in the lower measurements continues to very large positive fluctuations which then slowly relax to more typical levels. The time involved for the entire process is approximately $tU_\infty/\delta^* = 10$ or $tu_\tau^2/\nu = 1150$ in our case and $tU_\infty/\delta^* \approx 15$ or $tu_\tau^2/\nu \approx 50$ for the Blackwelder and Kaplan results.

This comparison is not meant to suggest that our results represent the "bursting" process which, by definition, is taken to be a wall region phenomenon. However, the similarities between our results and those obtained in the wall region of low-speed flows could be an indication that some aspects of the large-scale outer structure which would be basically Reynolds number independent are present in the latter measurements; or, alternatively, that flow processes similar to "bursts" exist in the outer region. In this regard, it is of interest to note that although the Blackwelder and Kalpan measurements

extend to $y^+ = 100$ (Fig. 5) in terms of wall variables, they alternatively span a distance of approximately δ^* or about 1/7 the boundary layer thickness. From Fig. 4 it can be seen that our measurements also extend to approximately one displacement thickness. It is clear from the present results (Fig. 4) and the results of Ref. 8, presented in Fig. 5, that there is a substantial amount of similarity in the instantaneous profiles when they are plotted in terms of y/δ^* instead of y^+. The region of the similarity extends in both to $y/\delta^* \approx 1$, while for the same conditions, a y^+ of 3750 exists for the present case and a y^+ of 100 prevails for the results of Ref. 8.

The strong influence that this flow structure exerts on the wall is clearly evident in Figs. 3 and 4. It can be seen from Fig. 3 that there is more than just a casual correlation between the wall measurements, particularly the wall shear, and the velocity fluctuations during this particular event. In Fig. 4 a definite correspondence can be seen between the sign and magnitude of the wall shear fluctuation and the slope of the fluctuation velocity profile as it has been drawn at the wall for each instant in time. Brown and Thomas[14] have suggested that the wall shear does respond in a "slowly varying" mode to the passage of the large-scale outer structure, and that the "bursting" process manifests itself as a high-frequency fluctuation with a definite phase relationship to the slowly varying component. (It is possible that this high-frequency small-scale component is missing in our shear measurement due to the size of the sensor used.) This may be an explanation for the high degree of correlation between our velocity measurements in the outer region and the shear fluctuations at the wall, but it is far from a closed question. The

correlation that exists is more than qualitative or in a time average sense as in the Brown and Thomas results. The inability to compare directly results from different experiments suggests that more standardized analyses be performed on data at different flow conditions in order to define more clearly the processes involved and their dependence on, say, Reynolds number.

Lateral Array Correlations

The bulk of the results that have been tested are for the lateral array of Fig. 2. The details of this research has been presented in Ref. 27.

Long time averages, normalized auto and cross correlations calculated for this array have been made and are presented in Ref. 27. This time delay to the maximum correlation between the wall-shear and velocity gave a result of -75 μsec for $y/\delta^* = 0.044$ and -160 μsec for $y/\delta^* = 0.31$. These delays can be interpreted in two ways. Using the distance between the measurements they yield an overall downward convection velocity of about 30 ft/sec in the first case and 90 ft/sec in the second. Together with the streamwise convection velocity $U_c/U_\infty \approx 0.68$ they could be taken to indicate the average orientation in the normal direction of disturbances or wave fronts in the flow. This interpretation leads to the conclusion that on the average the wavefronts lean forward in the flow and make an angle with the wall of 4° when $y/\delta^* = 0.044$ and 13° when $y/\delta^* = 0.31$. It is clear that in earlier interpretation the better estimate of what is happening very near the wall is given by the results for $y/\delta^* = 0.044$.

The correlations in the lateral direction show that there is much less choerence in this direction than has been found in either the streamwise or

normal directions. In almost all cases a significant correlation exists only, if at all, for the measurements adjacent to the reference. The exception to this seems to be the set of correlations between the velocity measurements at $y/\delta^* = 0.31$ (Fig. 6). In this case a relatively high coherence can be seen across all five measurements, perhaps indicating that at this height from the wall flow structures have a much wider lateral extent (i.e., on the order of $\Delta Z^+ \approx 5{,}000$). These tendencies were to be expected since other investigations, particularly those involving flow visualization, have shown that the wall region contains flow structures ("bursts") having lateral dimensions on the order of $Z^+ \approx 50$ and separations of $\Delta Z^+ \approx 100$, whereas the outer region is dominated by large scale structures with dimensions on the order of boundary layer thickness. The fact that we see any coherence at all in the wall measurements which are separated by a distance of $\Delta Z^+ \approx 1200$ is surprising. It may be an indication, together with the very high correlation between the wall-shear and velocity, that the large scale outer structure has a strong and direct influence on the wall.

The most important aspects of the processing performed on any of the measurements involves using the VITA variance analysis referred to earlier to conditionally sample the long data records and isolate temporal sequences believed to be associated with coherent flow structures. Ensemble averages formed from these conditional samples will depict, average or typical characteristics of the flow structures and the mean period between the samples or events can be used to estimate the frequency of occurrence of the structures.

It has been found that the VITA variance analysis has a weakness in terms of this latter estimate since the number of events detected is strongly dependent on the threshold level chosen in the scheme (see Ref. 19 for a definition of the terms used here). A plot of the mean period between detected events (nondimensionalized by δ^*/U_∞) versus threshold level is shown in Fig. 7 (Ref. 6) using various measurements as the detector or trigger to which the VITA variance analysis is applied. For reference, a line is drawn at $\bar{T}U_\infty/\delta^* = 35$ which corresponds to the commonly accepted value of $TU_\infty/\delta \stackrel{\sim}{\sim} 5$ for the "bursting" period. It can be seen that there is indeed a large variation in the number of events detected with different threshold levels. The variation with the measurement used as the trigger is partly to be expected since it has been found previously that the measured period does vary with distance from the wall. However, a certain amount of this variation (particularly) between the two wall measurements τ' and p') may be accountable to an improper choice of the averaging interval used in the scheme which is chosen on the basis of the frequency content of the signal being analyzed. In Fig. 7, the averaging interval was 150 μsec ($tU_\infty/\delta^* \stackrel{\sim}{\sim} 2$) for the shear and velocity and 80 μsec ($tU_\infty/\delta^* \stackrel{\sim}{\sim} 1$) for the pressure. For this ensemble averages discussed below, the threshold level was chosen so as to give a total number of events corresponding to approximately $TU_\infty/\delta^* = 35$.

Ensemble averages of the fluctuations using $u'(D)$, $p'(D)$ and $\tau'(D)$ as the triggers have also been performed for the case where the velocity probes are at $y/\delta^* = 0.044$. In all three cases the ensemble averages showed that a definite coherence exists in the normal and streamwise directions but very little, if any,

exists in the lateral direction. This agreed with the conclusions reached from the overall correlations presented in Ref. 27.

An attempt has been made to determine if the absence of any coherence in the lateral direction is due to noise which enters the ensemble averages because of random variations in the phase between the events at the trigger and at the measurement being averaged (see Ref. 26). A pattern recognition analysis is applied to determine this phase relationship for each of the samples in the ensemble averages. The samples are shifted so that the phase differences are made zero and then ensemble averaged. This has been done for the case where $\tau'(D)$ is used as the trigger with the addition of an intermediate step. This involves separating the set of events detected with this trigger into two groups depending on the phase relationship of such event with the corresponding event in $\tau'(C)$ as determined by the pattern recognition analysis. The corrected ensemble averages obtained for the set of events where a match is found at an earlier time (negative delay) in $\tau'(C)$ are presented in Fig. 8 and at a latter time (positive delay) in Fig. 9. The average delay by which the samples in a given ensemble have been shifted is shown for several of the averages in these figures. The marked improvement in the ensemble averages across the shear measurements in both cases shows that a coherence exists in the lateral direction which was previously obscured by considerable random phase "jitter". The fact that this coherence extends well beyond the $\Delta Z^+ \approx 50$ of wall region "bursts" may be a further indication that it is due to a direct response of the wall measurements to the passage of the large scale outer structures.

The fact that the events can be separated into two groups with opposite phase relationships across the lateral measurements is thought to be an indication of the "arrowhead" or "horseshow" type shape (see Fig. 2) that has been hypothesized for the large scale outer structures when looked at from above the wall of the boundary layer. It is clear that the phase relationship one would obtain among a set of lateral measurements would depend on which "leg" of the structure crosses the measurements. From the results of Figs. 8 and 9 it is possible to estimate the angles θ^+ and θ^- in Fig. 2 that each "leg" makes with the X-axis. To do this it is necessary to know the average streamwise convection velocity of the coherent structures along the wall. This has been estimated from previous measurements to be $U_c/U_\infty \approx 0.68$ (compared to $U_c/U_\infty \approx 0.6$ found for the overall convection velocity from the long time average correlations. Using this convection velocity and the average time delay between $\tau'(D)$ and $\tau'(C)$ in Fig. 8 the angle θ^+ is estimated (locally and on the average) to be 8°. The average delay in Fig. 9 also yields a θ^- of about 8°. These results compare favorably with an estimated angle of 6° found from the measurements of Fig. 2 at U_∞ = 675 ft/sec (Ref. 27). For low speed measurements (Refs. 28 and 15) this angle has been estimated to be anywhere from 18° - 22°. The significantly smaller angle obtained for the high speed flow may imply that the flow structures become more confined in the lateral direction as the free stream velocity is increased.

It can be seen from Figs. 8 and 9 that for both sets of events the phase relationship between $\tau'(D)$ and $u'(D)$ is such that the events are always seen

earlier in the velocity measurement. As discussed previously with regard to the long time average correlations, this can be interpreted either as <u>downward</u> convection of the flow structures or as <u>forward</u> leaning wavefronts. The average time delay between $\tau'(D)$ and $u'(D)$ for all the events of both Figs. 8 and 9 yields a downward convection velocity of about 30 ft/sec or wavefronts making an angle of approximately 4° with the wall. The fact that these results match those obtained from the long time average correlation implies that the coherent events, although taking up less than 1/5 of the total time, strongly control the overall characteristics of the flow in the normal direction. This is to be contrasted with the difference found between the streamwise convection velocity of the coherent events ($U_c/U_\infty = 0.68$) and the overall flow ($U_c/U_\infty = 0.60$), which implies that the faster moving coherent flow structures do not completely dominate the average flow in the streamwise direction.

The analysis performed between $\tau'(D)$ into two groups, was also carried out between $p'(D)$ and $p'(C)$ for the events detected with $p'(D)$ and between $u'(D)$ and $u'(E)$ for those detected with $u'(D)$. In terms of the angles θ^+ and θ^- of Fig. 2, the analysis of the lateral pressure measurements led to angles of about 7°. This agrees with the estimate made above from the shear. (In addition, however, the lateral pressure measurements show a great many events ($\approx$ 1/3) having approximately zero time delay between adjacemt measurements. This is not surprising in iteslf since the flow structure in Fig. 2 would show this sort of phase relationship near the centerline. What is puzzling is that the analysis of the lateral shear measurements does not show an equivalent large group of

events with zero time delay). The u'(D) - u'(E) analysis yielded a $\pm$ angle of about 10° which seems to indicate a spreading of the flow structures as one moves away from the wall.

As can be seen from the above, an analysis of these results has led to a collaboration of many of the conclusions reached concerning the nature of the coherent structures in the lateral and normal directions. Other analysis following the lines of the one discussed by Brown and Thomas (Ref. 14), was also performed in Ref. 15. The results show the same correlations for the positive delay events described with reference to Figs. 8 and 9.

COMMENTS ON RESEARCH AND DISCUSSIONS

The results obtained during this research for the coherent structure has been performed for a significantly higher Reynolds number than has been obtained previously ($Re_\theta = 1.1 \times 10^5$). The available data at high Reynolds number and comparable measurements made at much lower velocities has been made in order to clarify our picture of the structure. We also wish to make clear what we are concluding that our data shows.

It is obvious that our velocity measurements are made outisde of what has been called the wall region ($y^+ < 50$) with respect to the so-called "bursting" process at low Reynolds numbers. (In our case, a y^+ of 50 corresponds to a vertical distance from the wall of .006 inches.) However, the great similarity between the fluctuation velocity profiles were presented in Figs. 3 and 4, and those obtained by Blackwelder and Kaplan (USC A.E. Report No. 1-22, 1972, Fig. 5) at a much lower Reynolds number, seems to indicate that the detection scheme being used in the two cases triggers on the same type of flow structure and that this flow structure scales in the direction normal to the wall with δ^* and not ν/u_τ. This conclusion is supported by our shear measurement at the wall which shows an excellent correlation with the assumption we have made concerning the shape of the profiles from the wall to the first velocity measurement. In addition, the mean period between detected events when scales by δ^*/U_∞ is in good agreement with other estimates of the mean period between quasi-cyclic, recognizable patterns in both wall and boundary layer fluctuation measurements.

We would agree with the claim that further study is required to determine whether the flow phenomenon which our profiles represent is part of the

large-scale structure of the outer boundary layer, or is a representation of a "bursting" process which exists in high-velocity, high-Reynolds number flows. However, we disagree with the argument that the Blackwelder and Kaplan profiles necessarily depict the wall layer "bursting" process. If it should be determined that our profiles represent part of a large-scale structure which extends down to the wall, the Blackwelder and Kaplan results would have to be reexamined in light of the arguments made above concerning the similarity with our data. In particular, it should be emphasized that while a comparison of the vertical scale of the fluctuation profiles in the two cases shows a great discrepancy in terms of the parameter $y^+(=yu_\tau/\nu)$, an almost exact agreement occurs when the profiles are looked at in terms of y/δ^*.

In order to verify some of our results with low speed data, tests were also performed at low speed in order to duplicate the results of other investigations. This has also been done and reported in Ref. 28.

Our research has contributed significantly to the high Reynolds number range and have identified areas of discrepancy from the low speed data. One must realize that at high speeds when the sublayer is of the same order as the roughness of the surface, it is possible that the entire turbulent boundary layer is dominated by the outer structure. The relationship or interaction between this large scale outer structure and the turbulent "bursts" is still not clearly defined. It is possible that with smaller instrumentation, that could be made available in the future, a better resolution of the events could be achieved.

It seems from the available literature that a significant emphasis is being placed on low velocity experiments in this area, and very little work is being conducted in high-velocity, high-Reynolds number flows.

The capability of achieving a facility with a large Reynolds number capability, and a turbulent boundary layer that is free from artificial tripping, is essential for performing research in this area.

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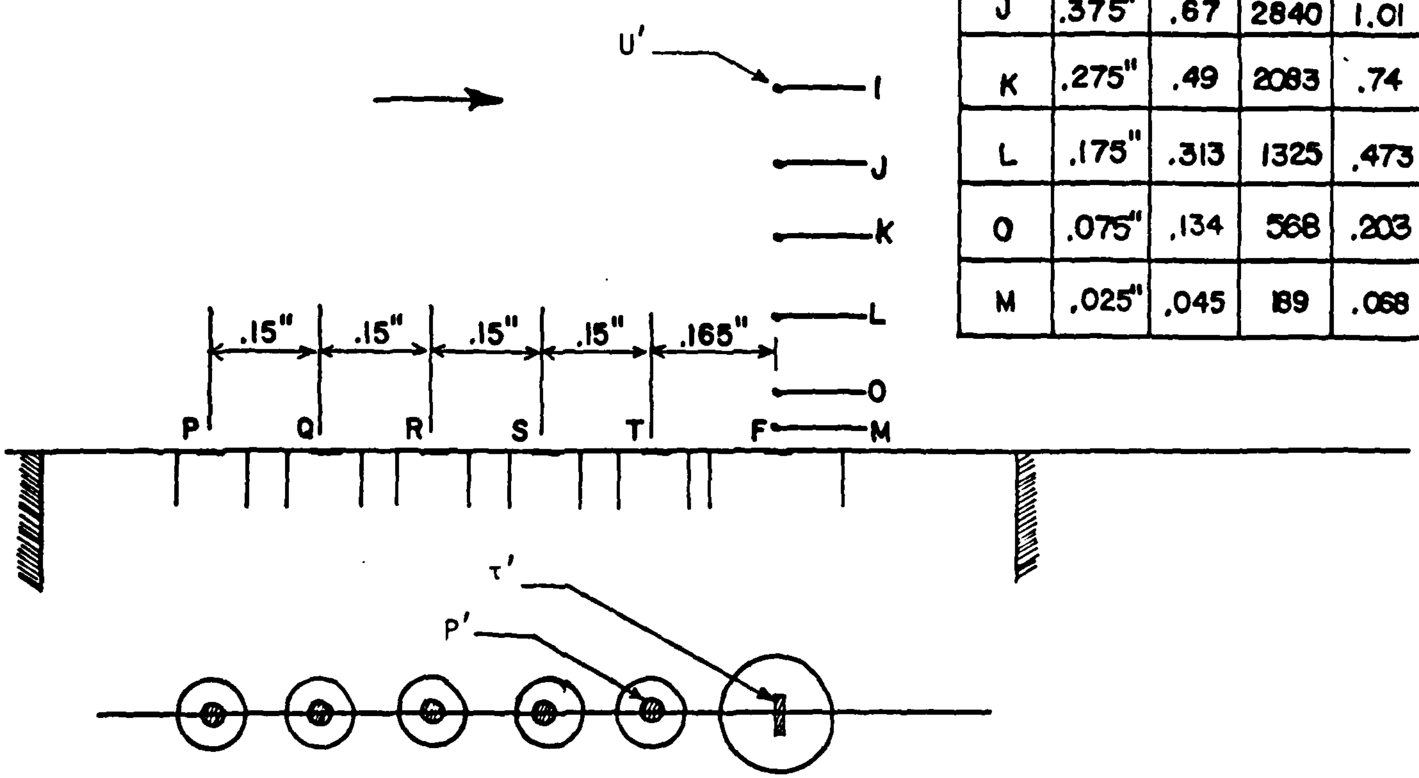
X/D	15.5	20.5	9.	15.5	31.	31.
M_∞	0.0263	0.0296	0.063	0.067	0.072	.64
U_∞ (ft/sec)	29.6	32.6	69.0	73.0	79.0	675
q_∞ (psi)	0.0068	0.0086	0.039	0.046	0.054	2.9
δ (in)	2.7	3.5	2.15	3.0	$\approx$ 5.5	4.0
δ^* (in)	0.39	0.497	0.265	0.37	$\approx$ 0.8	0.564
θ (in)	0.31	0.387	0.206	0.29	$\approx$ 0.6	0.384
Re_θ	4.62×10^3	6.56×10^3	8.45×10^3	1.25×10^4	2.82×10^4	1.08×10^5
ν/u_τ (in)	1.66×10^{-3}	1.09×10^{-3}	$.69 \times 10^{-3}$	$.67 \times 10^{-3}$	$.68 \times 10^{-3}$	1.32×10^{-4}
ν/u_τ^2 (μsec)	120	51.6	24.0	22.5	23.0	0.62
$(u'/u)_\infty$	0.005	-	-	0.005	0.021	0.008

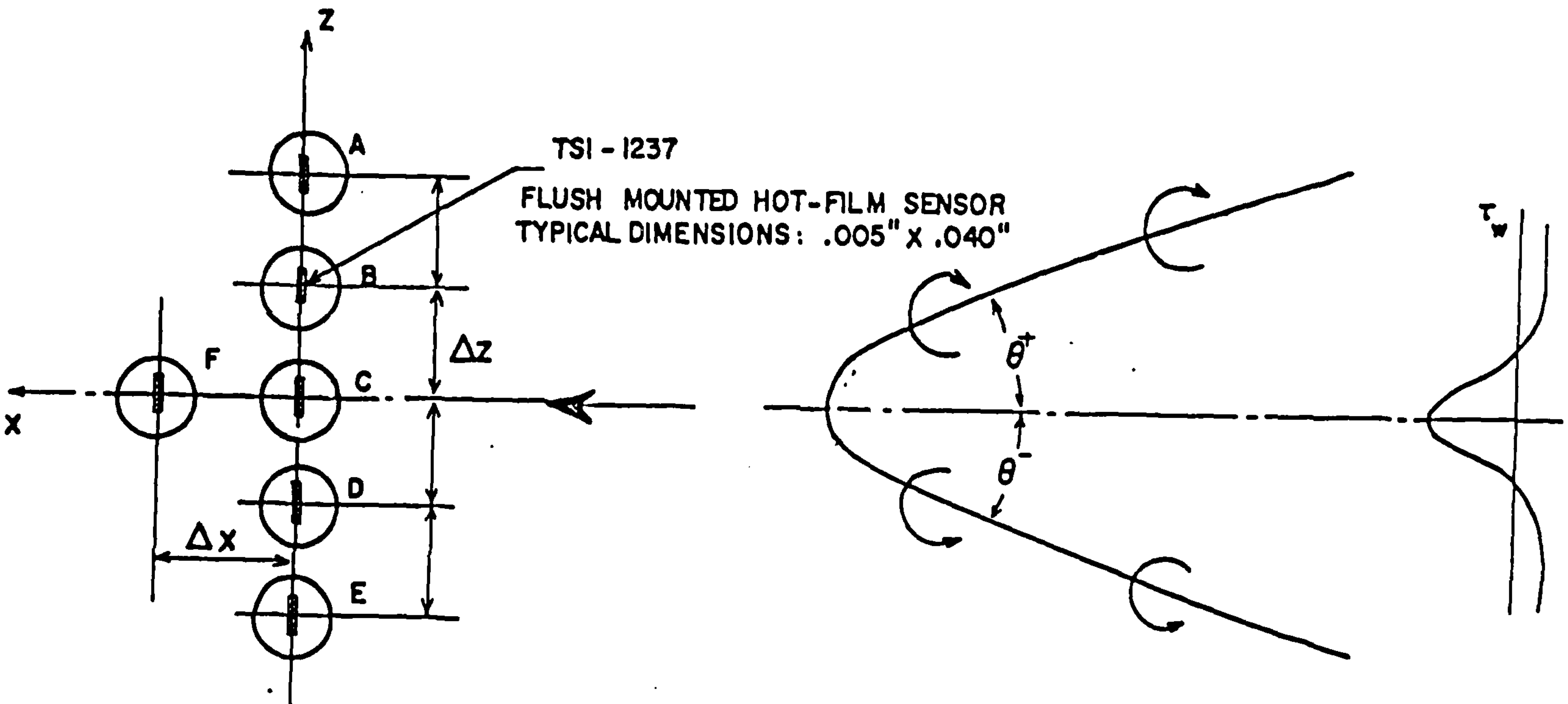
TABLE I

MEAN FLOW PARAMETERS AT SEVERAL STATIONS FOR THREE TEST CONDITIONS



U_∞ (ft/sec)		675		73		32.6	
	y	y/δ^*	y^+	y/δ^*	y^+	y/δ^*	y^+
I	.475"	.85	3800	1.28	710	.95	436
J	.375"	.67	2840	1.01	560	.75	344
K	.275"	.49	2083	.74	410	.55	252
L	.175"	.313	1325	.473	261	.350	160
O	.075"	.134	568	.203	112	.150	69
M	.025"	.045	189	.068	37	.050	23

FIG. 1 SKETCH OF INSTRUMENTATION LAY-OUT INCLUDING TABLE OF NON-DIMENSIONAL DISTANCES FROM WALL



U_∞ (ft/sec)		675		75		32.6	
Δx	Δz	Δx^+	Δz^+	Δx^+	Δz^+	Δx^+	Δz^+
0.2"	0.157"	1540	1208	299	234	182	143

(PROPOSED PLAN VIEW OF LARGE-SCALE OUTER STRUCTURE FROM THOMAS, REF. 20)

FIG. 2 LATERAL ARRAY OF FLUSH HOT-FILM SHEAR SENSORS

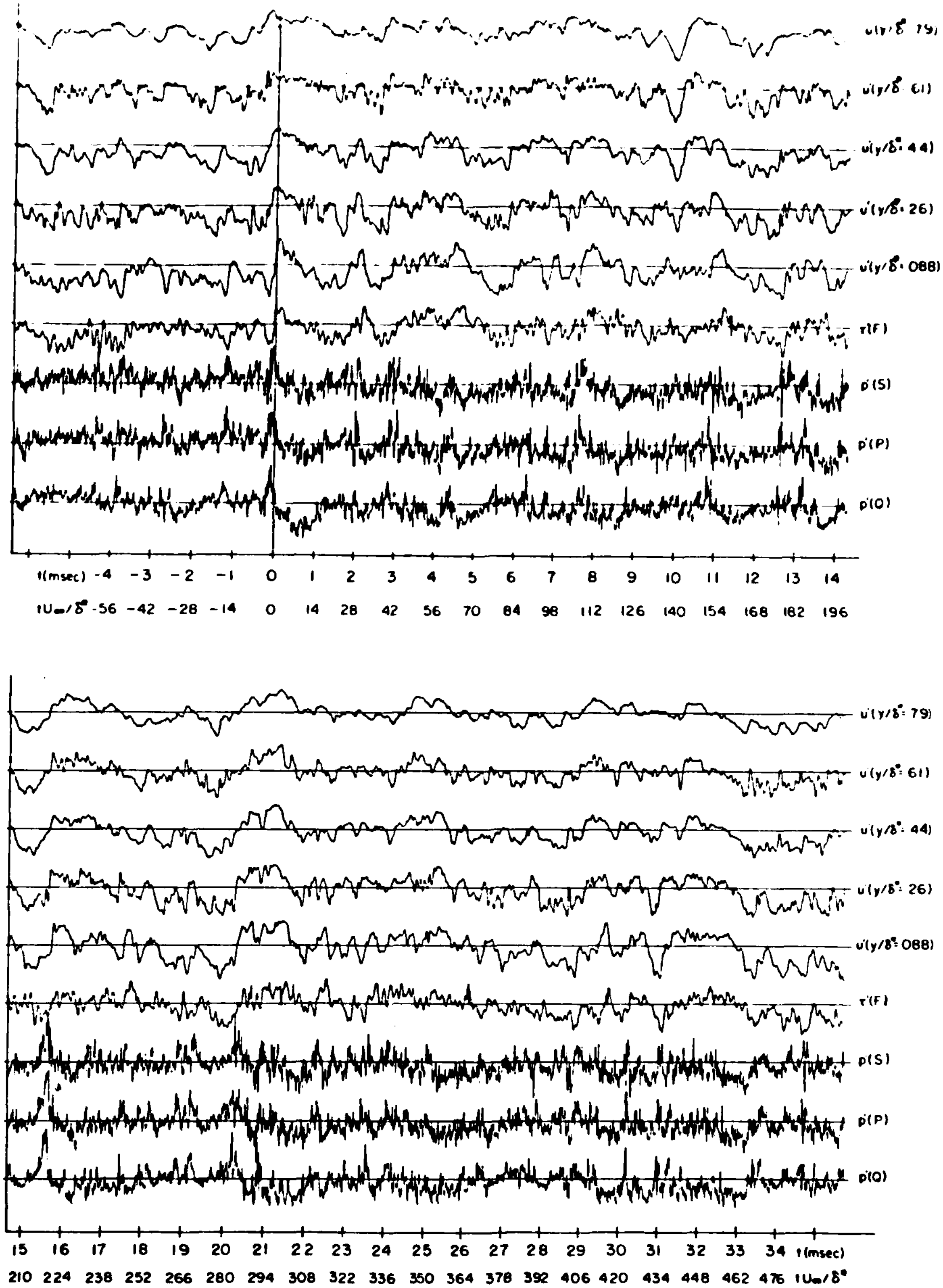


FIG. 3 SAMPLE PLOT OF DIGITIZED DATA SHOWING FLUCTUATING VELOCITIES, SHEAR, AND PRESSURES

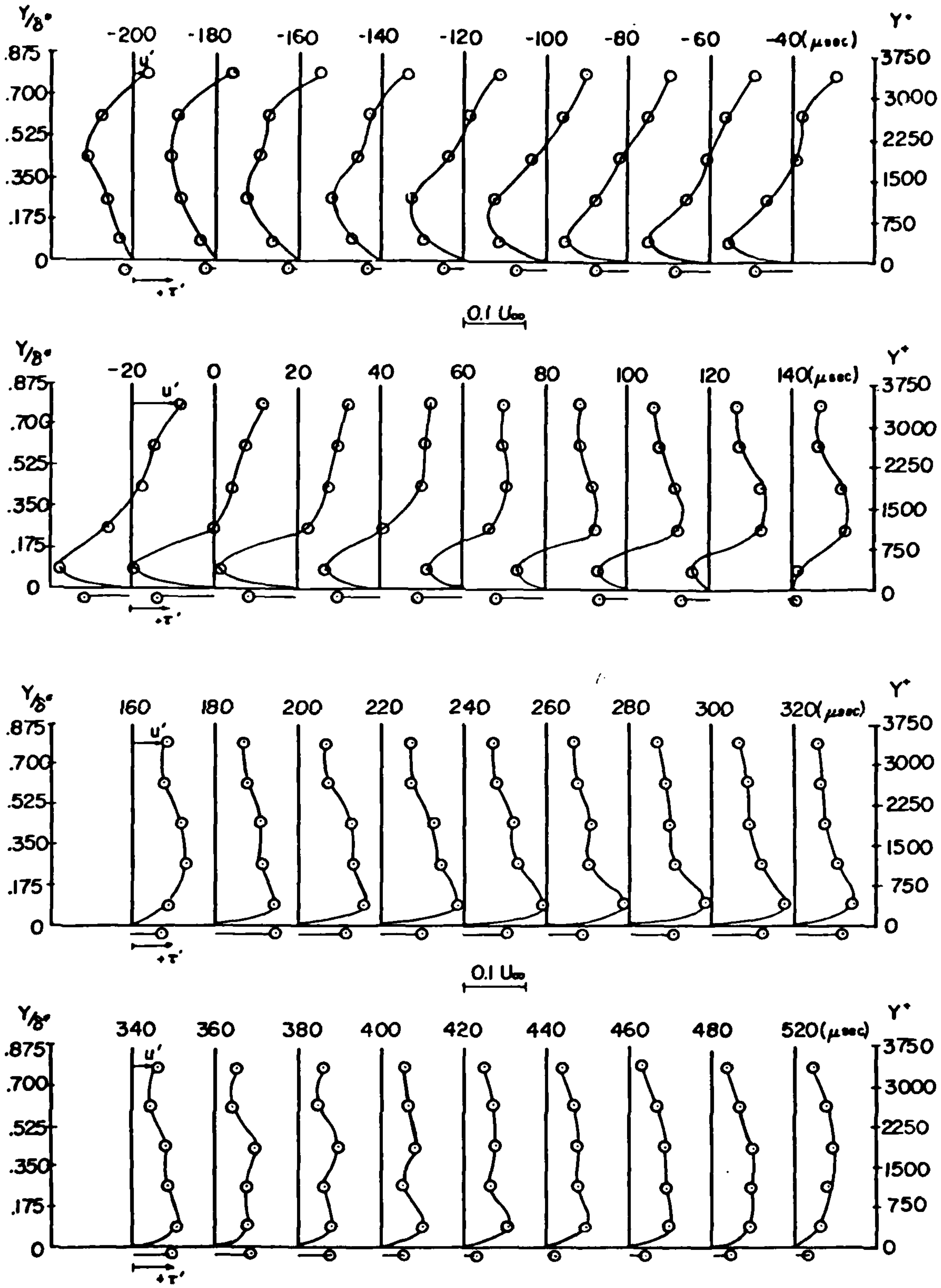


FIG. 4 SEQUENCE OF PERTURBATION VELOCITY PROFILES AND FLUCTUATING SHEAR DURING A BURST

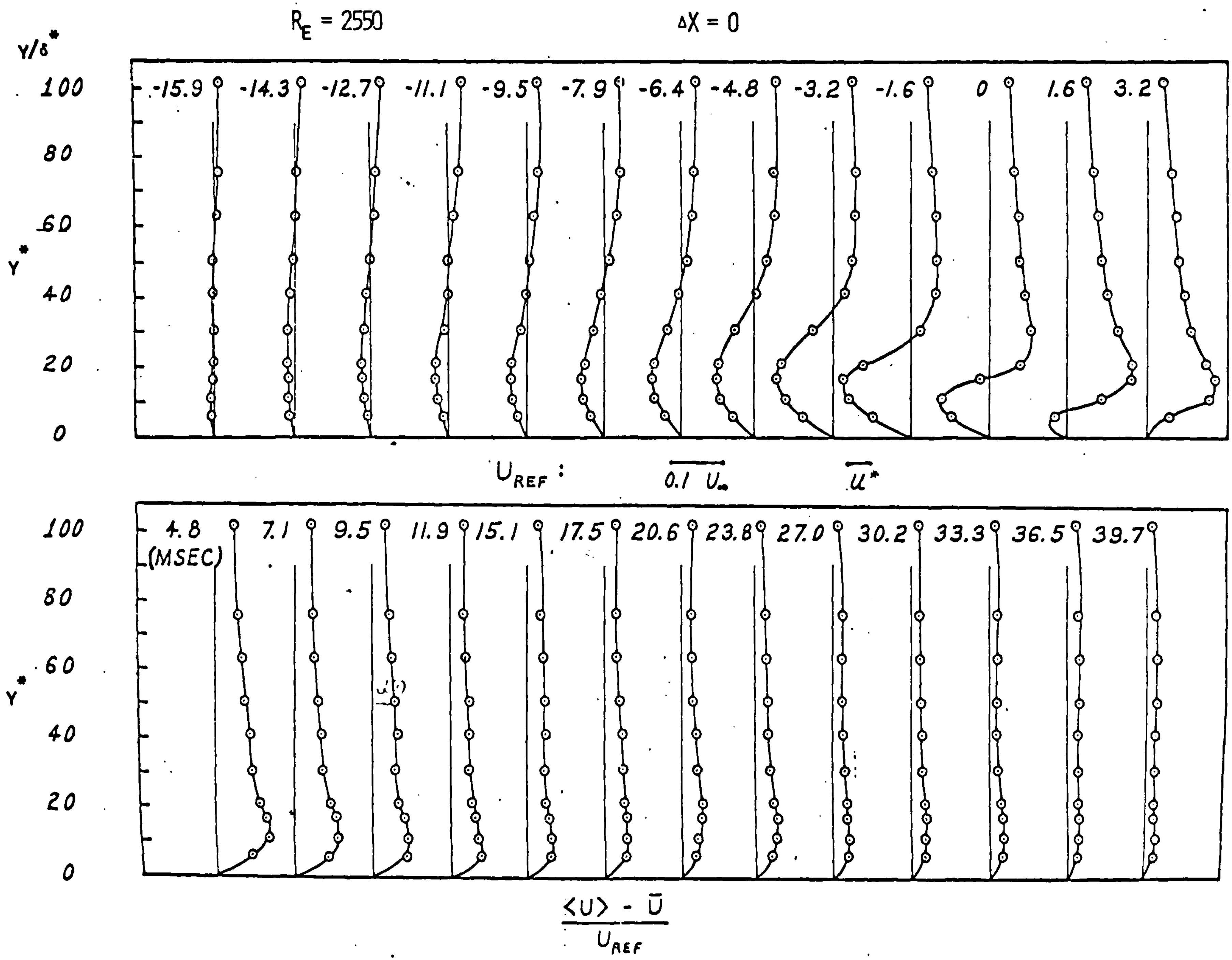
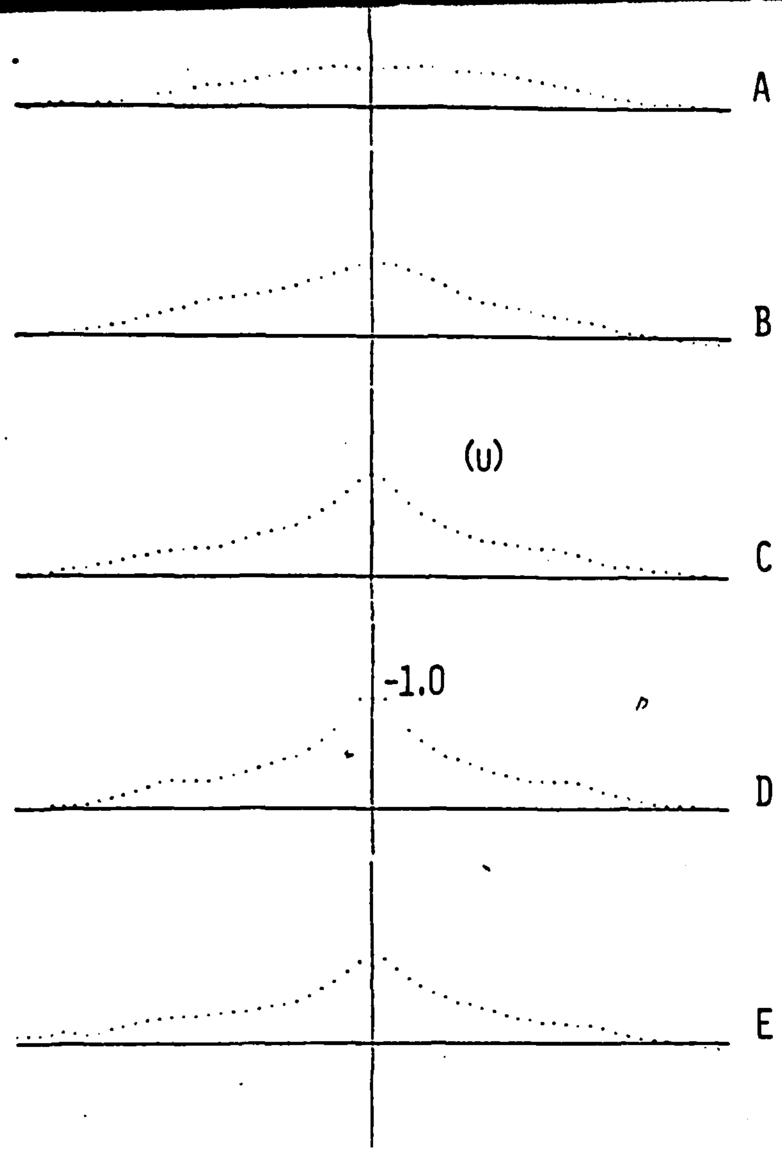
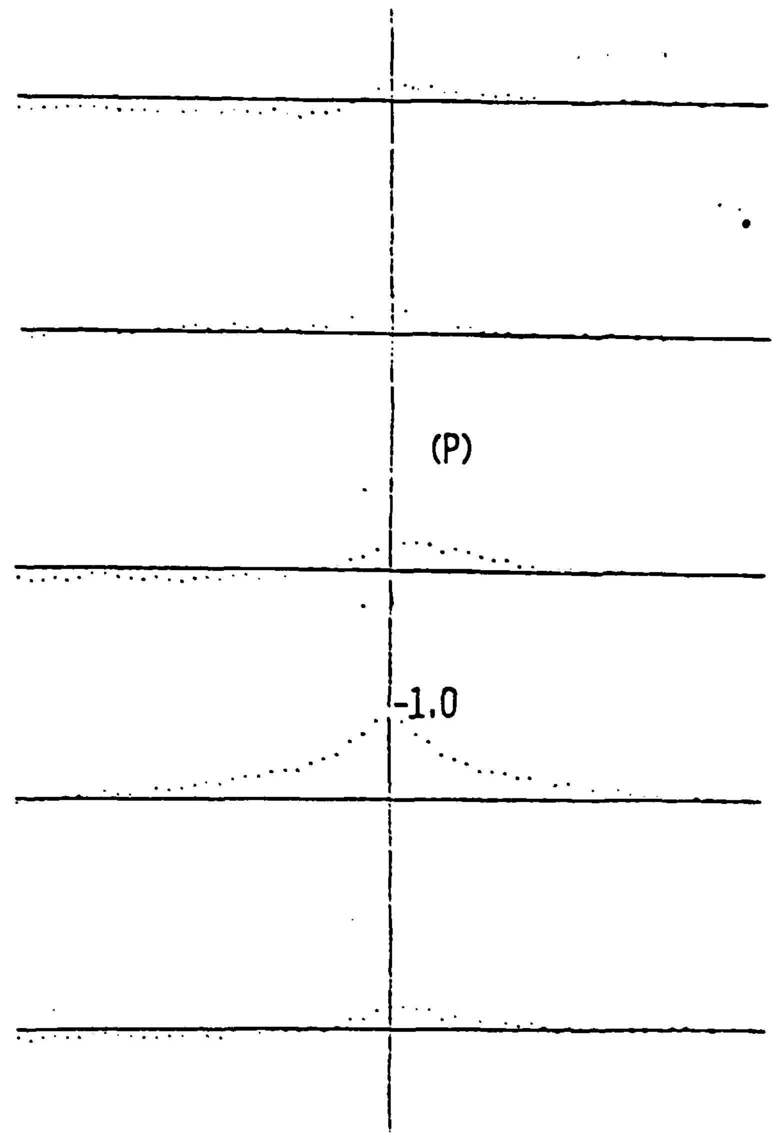


FIG. 5 PERTURBATION VELOCITY PROFILES MEASURED DURING THE BURSTING PERIOD AT X = 0



B) REFERENCE: u'(D)



C) REFERENCE: P'(D)

FIGS. 6 LONG TIME AVERAGE CORRELATIONS FOR THE FULL LATERAL ARRAY WITH THE VELOCITY PROBES AT $y/\delta^* = 0.31$ (U_∞ = 675 DT/SEC)

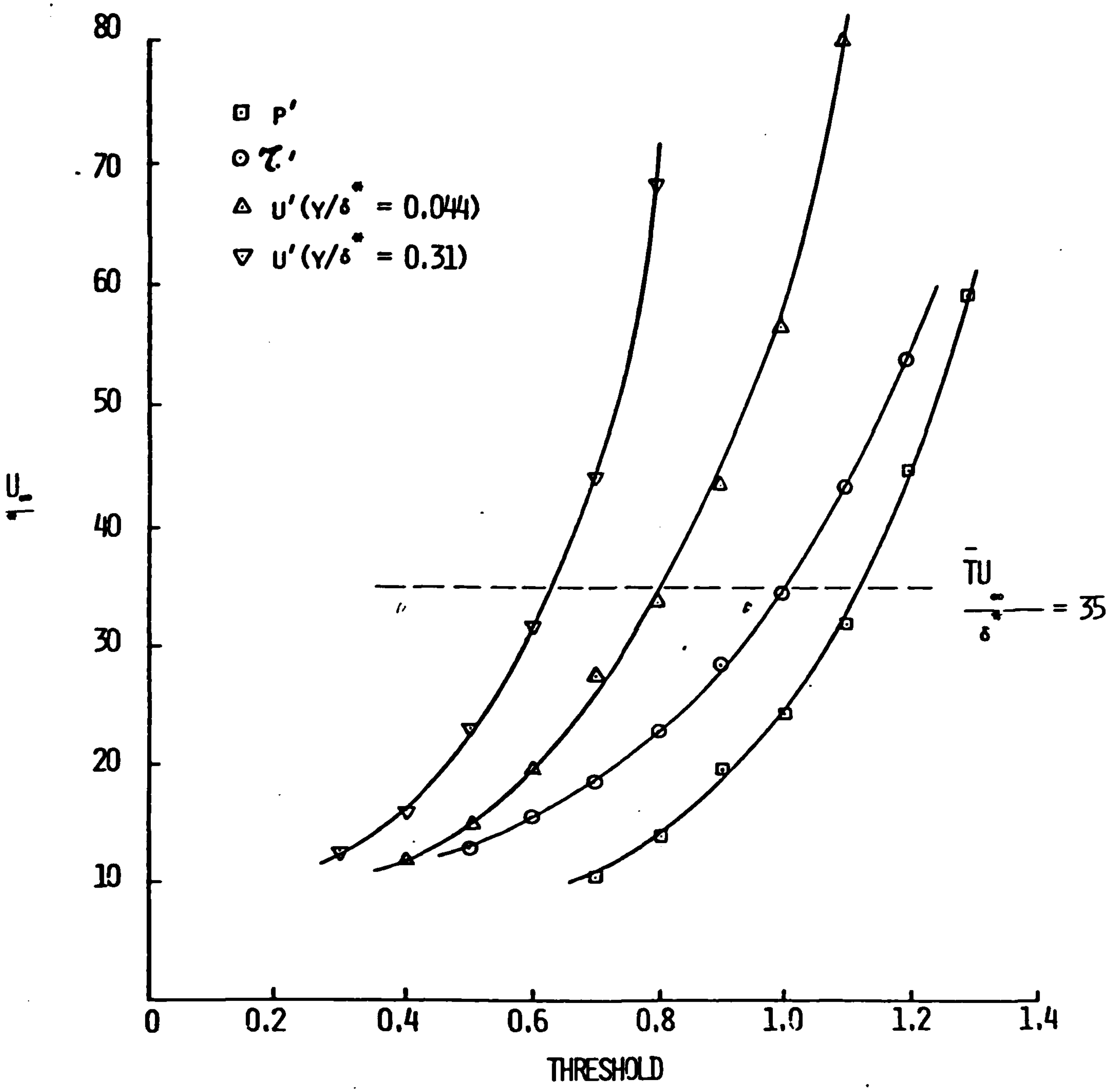


FIG. 7 VARIATION OF THE MEAN PERIOD BETWEEN DETECTED EVENTS WITH THRESHOLD LEVEL IN THE VITA VARIANCE ANALYSIS USING VARIOUS MEASUREMENTS AS THE DETECTOR OR TRIGGER.

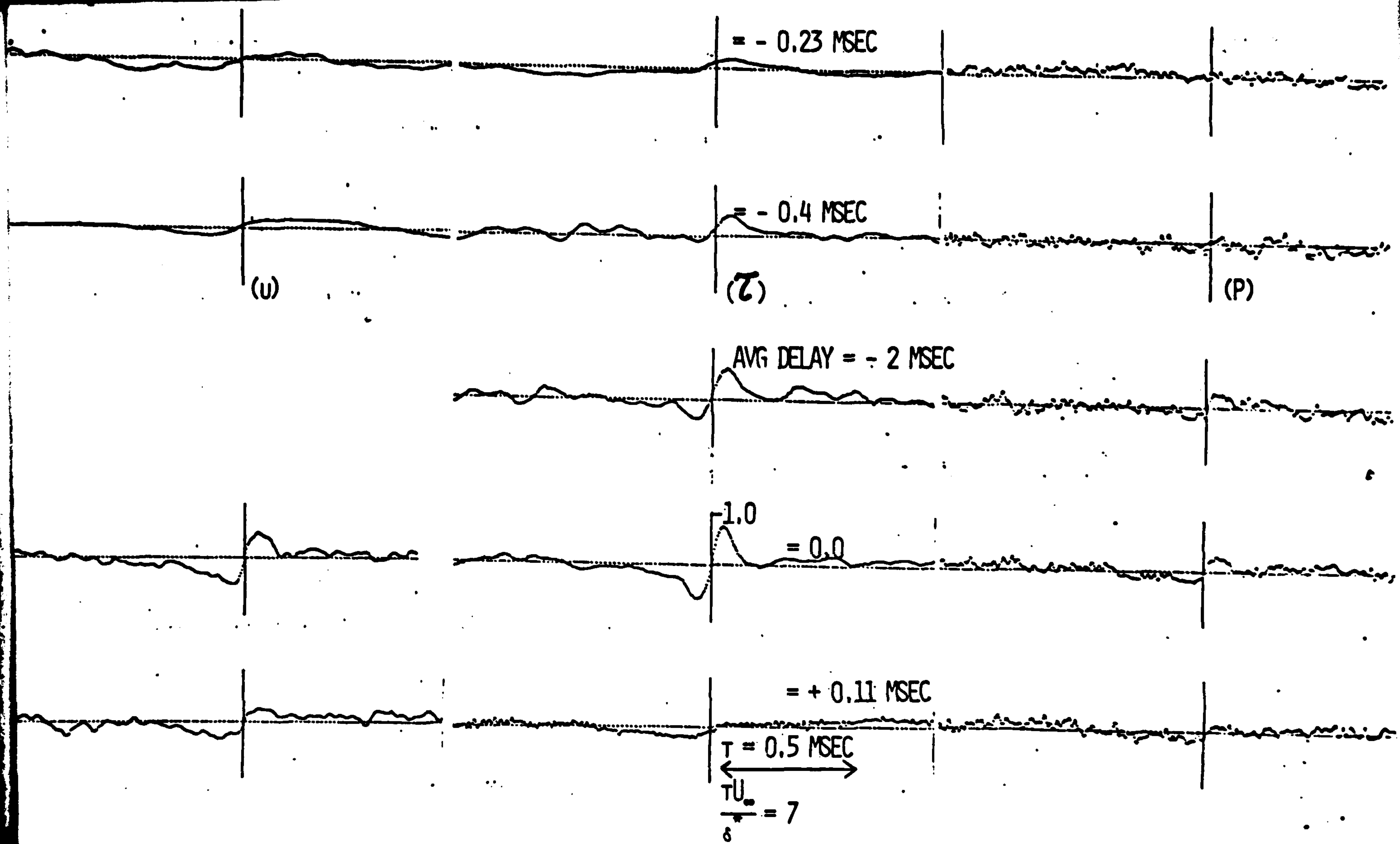


FIG. 8 ENSEMBLE AVERAGED VELOCITY, SHEAR AND PRESSURE FLUCTUATIONS FOR THE FULL LATERAL ARRAY AFTER CORRECTION FOR PHASE "JITTER" (U_∞ = 675 FT/SEC, u' @ y/δ^*, = 0.044, TRIGGER: τ'(D)/EVENTS WITH NEGATIVE DELAYS BETWEEN τ'(D) AND τ'(C)

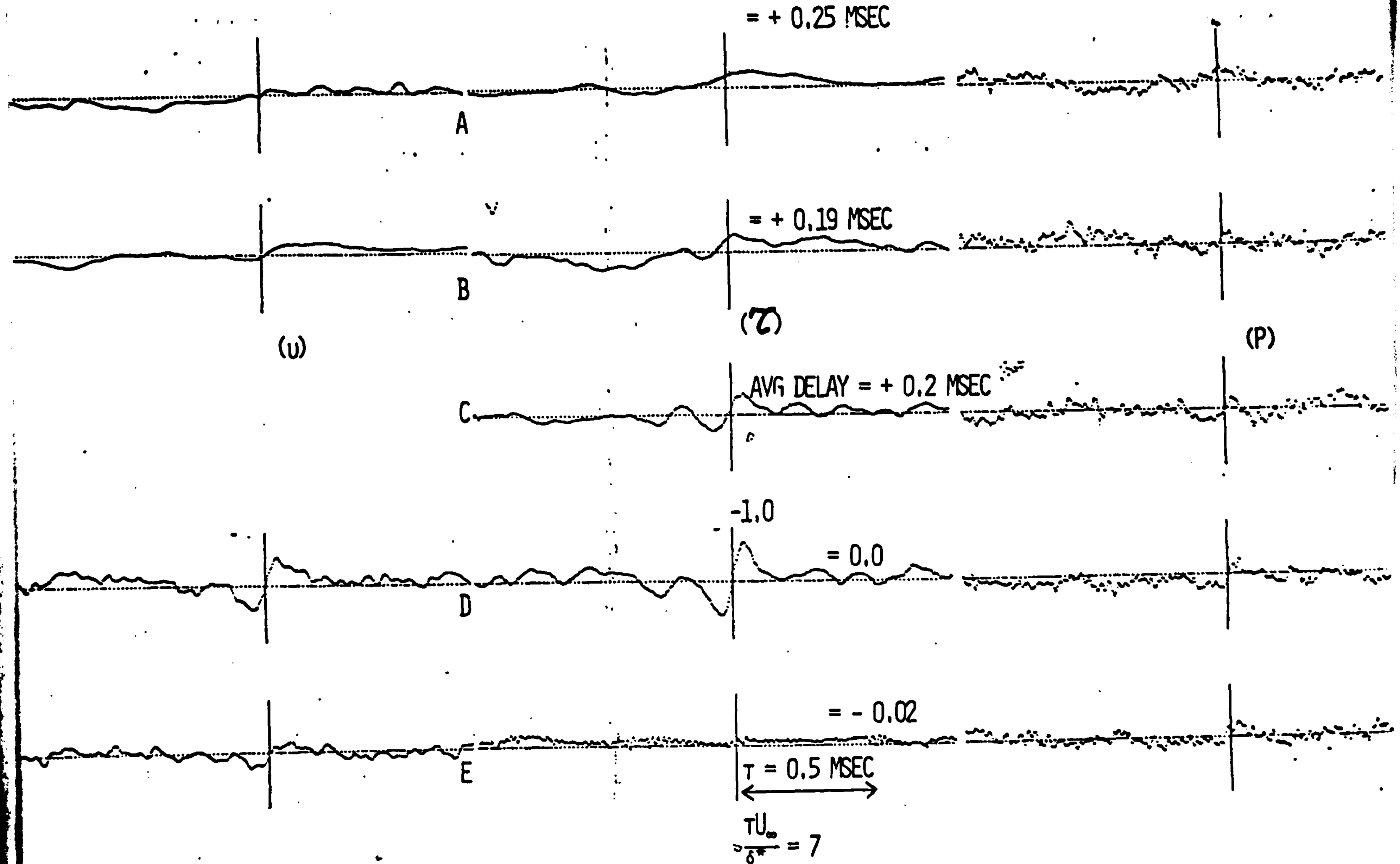


FIG. 9 ENSEMBLE AVERAGED VELOCITY, SHEAR AND PRESSURE FLUCTUATIONS FOR THE FULL LATERAL ARRAY AFTER CORRECTION FOR PHASE "JITTER" (U_∞ = 675 FT/SEC, u' @ y/δ^* = 0.044, TRIGGER: τ'(D)/EVENTS WITH POSITIVE DELAYS BETWEEN τ'(D) AND τ'(C)

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: AFOSR-TR- 81 -0759	2. GOVT ACCESSION NO. [illegible]
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): THE INVESTIGATION OF THE PROPAGATION MECHANISM OF PRESSURE FLUCTUATION IN TURBULENT FLOW	5. TYPE OF REPORT & PERIOD COVERED: FINAL FEBRUARY 1981
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): VICTOR ZAKKAY, VINCENT BARRA	8. CONTRACT OR GRANT NUMBER(s): AFOSR-79-0128
9. PERFORMING ORGANIZATION NAME AND ADDRESS: NEW YORK UNIVERSITY, DEPT OF APPLIED SCIENCE, WESTBURY, NY 11590	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 2307/A2 61102F
11. CONTROLLING OFFICE NAME AND ADDRESS: AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA, BUILDING 410, BOLLING AFB, DC 20332	12. REPORT DATE: FEBRUARY 1981
	13. NUMBER OF PAGES: 23+9 Figures
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

TURBULENCE
COHERENT STRUCTURES
PRESSURE FLUCTUATIONS
BOUNDARY LAYERS
HIGH REYNOLDS NUMBER TURBULENCE

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A summary of the work performed under Contract AFOSR-79-0128 is given within this report. Under this Contract, the Antonio Ferri Laboratories at New York University has built a one foot induction wind tunnel for the purpose of studying the coherent structure of turbulence. Simultaneous measurements of velocity, wall pressure and wall-shear fluctuations were made on the wall of a one foot pipe in a range of velocities from 30 to 700 ft/sec. The results presented here were obtained for flow conditions which differ significantly from those in previous studies. For the majority of the tests, the free

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stream velocity is in ti high subsonic regime, and the R nolds number is an order of magnitude higher than that for which the coherent structure has previously been investigated. The measurements were made on the wall of an axially symmetric one foot test section in order to insure true two-dimensionality of the flow. The results of the above research has been reported in six technical reports which have been published in the open literature. a summary of this work is presented in this report

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